

Variable stars in the open cluster NGC 2141 *

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Abstract We report the results of a search for variable stars in the open cluster NGC 2141. Ten variable stars are detected, among which nine are new variable stars and they are classified as three short-period W UMa-type eclipsing binaries, two EA-type eclipsing binaries, one EB-type eclipsing binary, one very short-period RS CVn-type eclipsing binary, one d-type RR Lyrae variable star, and one unknown type variable star. The membership and physical properties are discussed, based on their light curves, positions in the CMDs, spatial locations and periods. A known EB-type eclipsing binary is also identified as a blue straggler candidate of the cluster. Furthermore, we find that all eclipsing contact binaries have prominently asymmetric eclipses and O’Connell effect (O’Connell 1951) which increases with the decrease of the orbital periods. This suggests that the O’Connell effect is probably related to the evolution of the orbital period in short period eclipsing binary systems.

Key words: binaries: general — open clusters and associations: individual (NGC 2141)—
stars: variables: general

1 INTRODUCTION

This paper is a contribution to our ongoing program of a search for variable stars in open clusters (Zhang et al. 2002, 2004; Luo et al. 2009, 2012b). One of our main goals is to study the stellar evolution via the census of variable stars in the open clusters. The stars in an open cluster have a approximately same age and chemical abundances, in which the statistical properties of variable stars can put some stronger constraints on the stellar theoretical models (Kim et al. 2000) and the unresolved physical processes like the mass transfer, common-envelope ejection, mass loss, angular momentum loss, etc (Jiang et al. 2009; Pietrzyński et al. 2009, 2013; Ivanova et al. 2013). In addition, they were also used to measure the age and distance of the hosted clusters and provide some hits on the cluster dynamical evolution. (Meibom et al. 2009).

NGC 2141 is an old galactic anticenter open cluster. The coordinates of the cluster center are $RA(J2000)=06^h02^m58^s.2$ and $Dec(J2000)=+10^\circ26'39''$ ($l = 198^\circ.75, b = -5^\circ.79$) (Carraro et al. 2001). Burkhead et al. (1972) presented the first photoelectric and photographic observations and concluded that NGC 2141 is of a late intermediated age, a mean color excess of $E(B - V) = 0.30$ and a distance modulus of $m - M = 14.1$. Rosvick (1995) then performed a new optical VI and near-infrared JH photometry. Compared with the theoretical isochrones, the age and metallicity were estimated to be $t = 2.5$ Gyr and $Z = 0.006$. The corresponding color excess and distance modulus were $E(B - V) = 0.35 \pm 0.07$ and $m - M = 14.16 \pm 0.16$. Carraro et al. (2001) acquired a deeper BV and JK photometry in a small area round the cluster center, from which they derived a slightly larger reddening ($E(B - V) = 0.4$) and a slightly shorter distance (~ 3.8 kpc). The latest photometric data for this cluster have been presented by Donati et al. (2014), who concluded that NGC 2141 is an old open cluster with age in the range 1.25 and 1.9 Gyr, $E(B - V)$ between 0.36 and 0.45, $(m - M)_0$ between 11.95 and 12.21 and subsolar metallicity. NGC 2141 is still an interesting target for the study of variable stars. Much deeper photometry showed that the cluster has a very rich binary population and appears the mass segregation (Carraro et al. 2001; Donati et al. 2014). Although many variable candidates in NGC 2141 were reported, the detailed information is not yet known (Kissinger & Kafka 2005; Widhalm & Kafka 2006). Therefore, we carried out a new time-series photometry for the open cluster NGC 2141 to detect the variable stars. Observations and data reductions are described in Section 2; identification of variable stars is presented in Section 3; their physical properties are discussed in Section 4; and a summery is followed in Section 5.

2 OBSERVATIONS AND DATA REDUCTIONS

All photometric observations of the open cluster NGC 2141 were carried out on four nights in Jan 4–7, 2011, using the Lijiang 2.4m telescope in Yunnan Astronomical Observatory, Chinese Academy of Sciences. We used the Yunnan Faint Object Spectrograph and Camera (YFOSC) to take the data, which are equipped with a 4096×2048 CCD camera and two filter systems: standard johnson-cousin-bessel $UBVRI$ and SDSS $ugriz$. It provides two observational modes: spectra and image. We adopted the image mode, under which the effective pix is 2048×2048 and the field of view is about $10' \times 10'$. The Standard Johnson-Cousin-Bessel V filter was chosen and the exposure times were set to be 360 second. In total, we acquired 230 V -band frames. An additional set of $UBVRI$ photometry of the cluster was obtained in Jan 6, 2011, when it satisfied the photometric sky conditions. Two Landolt standard fields: SA 95 and SA 98 (Landolt 1992) and a Stetson photometric standard field: open cluster M67 (Stetson 2000) were also observed to construct photometric standards.

The raw images were de-biased and flat-fielded with the IRAF-CCDPROC package. The instrumental magnitudes of stars in the CCD images were then extracted using the point-spread function fitting program in the IRAF-DAOPHOT package. The instrumental magnitudes in $UBVRI$ bands were corrected by using IRAF-DAOGROW package and converted to standard system with the following transformation equations:

$$B = b - 1.277 \pm 0.025 + (0.031 \pm 0.004)(b - v) - (0.233 \pm 0.019)X, \quad (1)$$

Table 1 Parameters of variable stars in the field of NGC 2141

Star RA	Dec	V_{max}	$B - V$	$V - R$	$V - I$	Radius	Period T_0	Type	Memb
ID (J2000)	(J2000)	(mag)	(mag)	(mag)	(mag)	(arcmin)	(days)	(days)	
V1	06:03:03.85	10:27:15.68	15.046	0.604	0.408	0.924 1.78	0.6233 68.1022	EB	likely
V2	06:03:12.33	10:31:09.82	16.857	0.820	0.528	1.049 5.42	0.3984 70.1991	RRd	unlikely
V3	06:02:51.90	10:25:07.05	17.230	0.894	0.561	1.084 2.52	1.3665 68.2472	EA	likely
V4	06:02:49.37	10:26:14.71	17.981	0.872	0.536	1.054 1.95	4.9878 70.3432	EA	likely
V5	06:02:52.54	10:26:15.50	18.213	0.987	0.589	1.157 1.49	0.3261 67.3106	EW	likely
V6	06:02:55.28	10:24:58.06	18.264	0.924	0.579	1.193 3.98	0.3112 67.1370	EW	likely
V7	06:02:51.52	10:30:54.07	19.031	0.975	0.663	1.275 3.79	0.5529 70.1531	EB	likely
V8	06:02:56.72	10:23:22.77	19.111	1.134	0.723	1.466 2.44	0.2305 70.1278	RS CVn	likely
V9	06:02:50.20	10:25:22.10	19.231	1.362	0.943	1.712 2.59	0.2432 70.0987	EW	unlikely
V10	06:03:14.57	10:30:34.05	16.120	1.056	0.663	1.329 5.48			likely

Notes: $T_0(HJD - 2455500)$ denotes the phase zero epoch.

$$R = r - 0.991 \pm 0.009 - (0.103 \pm 0.004)(v - r) - (0.095 \pm 0.007)X, \quad (3)$$

$$I = i - 0.624 \pm 0.024 + (0.019 \pm 0.005)(v - i) - (0.065 \pm 0.018)X, \quad (4)$$

where b, v, r and i are the instrumental magnitudes, B, V, R and I denote the standard magnitudes, as well as X is the airmass.

3 IDENTIFICATION OF VARIABLE STARS

For the purpose of searching for variable stars, we made a differential photometry for each star detected in V -band images. Followed [Zhang et al. \(2002\)](#), an image with the best seeing and highest signal to noise ratio was chosen to be the reference frame, from which we then iteratively picked up about one hundred non-variable bright stars as the reference stars. With these reference stars, the magnitudes of all stars in images were corrected with respect to the reference frame.

We then used two selection methods to identify variable candidates from above differential light curves. Firstly, we selected the stars whose light curves show the larger deviations than those with similar brightness as candidates. Then, we calculated the Stetson J -index ([Stetson 1996](#)) of stars and picked up stars with large J -index as candidates. Finally, we visually inspected the light curves of variable candidates and rejected spurious variables and those showing small variability and chaotic light variations. In total, we identified ten new variable stars in the field of NGC 2141. They are temporarily named as V1 – V10. [Figure. 1](#) displays their spatial locations in the observed CCD field and [Table. 1](#) gives their coordinates and physical parameters derived from the color magnitude diagrams (CMD) and light curves.

4 PHYSICAL PROPERTIES OF VARIABLE STARS

4.1 Cluster membership

In general, the determination of the cluster membership mainly depends on the proper motions and radial velocities. However, there is not any report on them. In this paper, we discuss their cluster memberships

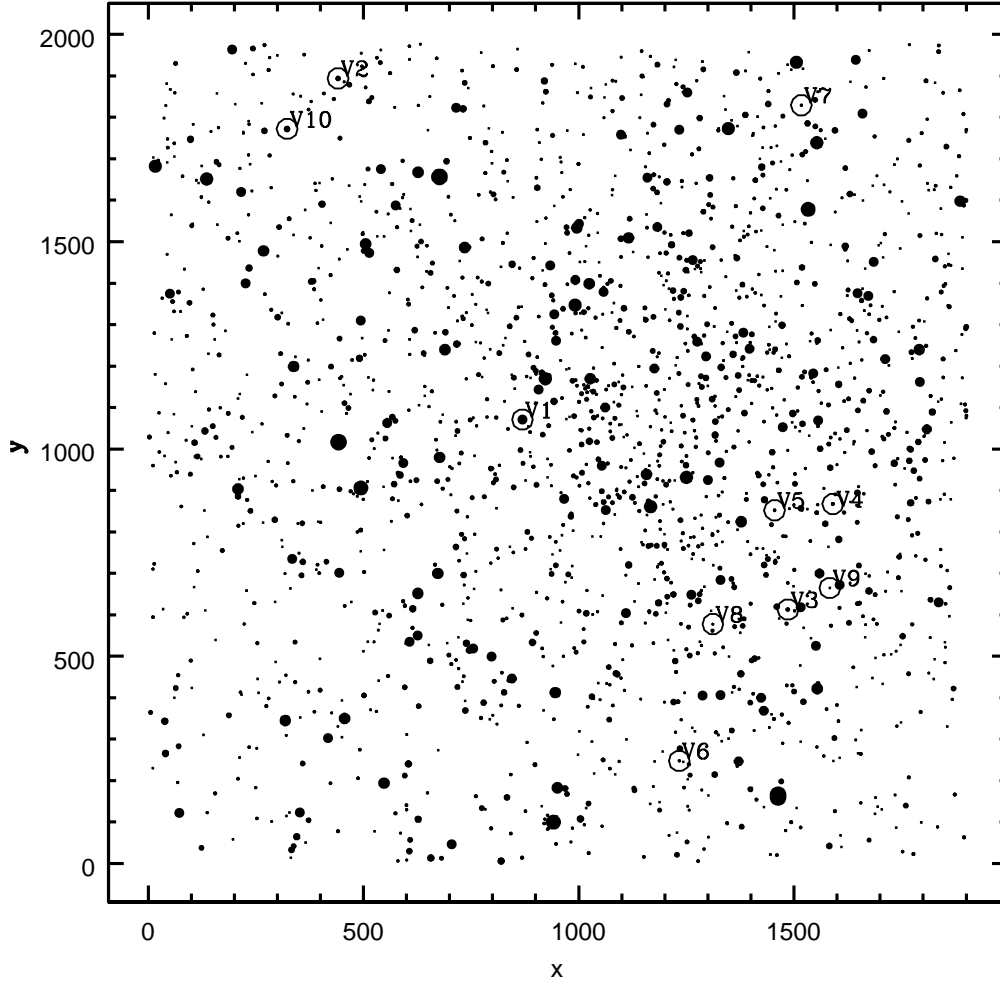


Fig. 1 Observed CCD field of the open cluster NGC 2141 and locations of variable stars

To derive the cluster memberships of variable stars from the spatial locations, we derived the physical parameters of the cluster. First of all, we determined the center of the clusters by finding the maximum surface number density of stars in the cluster field. Here, stars with $V \leq 20$ were just considered. The cluster center was roughly determined by the pixel coordinate (1234,1080) in our reference CCD frame. Then, we set a series of concentric rings around the center. The width of rings was set to be 106 pix (~ 30 arcsec). The stellar radial density profile was derived by counting the number of stars per area in each concentric ring and is shown in Fig. 2. The error bars were determined on the assumption that the number of stars in each rings follows the Poisson statistical distribution. We adopted a two-parameter King model (King 1966) to fit the radial density profile

$$\sigma(r) = \sigma_{bg} + \frac{\sigma_0}{1 + \left(\frac{r}{r_c}\right)^2}, \quad (5)$$

where σ_{bg} is the background field density, σ_0 the central density of stars, and r_c the core radius of the cluster. A best fitting model is shown by the solid line in Fig. 2 and gives that $\sigma_{bg} = 5.3 \pm 3.2$ stars arcmin $^{-2}$, $\sigma_0 = 42.5 \pm 3.5$ stars arcmin $^{-2}$ and $r_c = 2.1 \pm 0.3$ arcmin. The distances of variable stars from the center are given in Table. 1. We could deduce from Fig. 2 that our observed field is inside the cluster, which implies that all variable stars are probably the cluster members in the spatial locations.

In addition, CMDs can also provide some very important constraints on the cluster membership of the

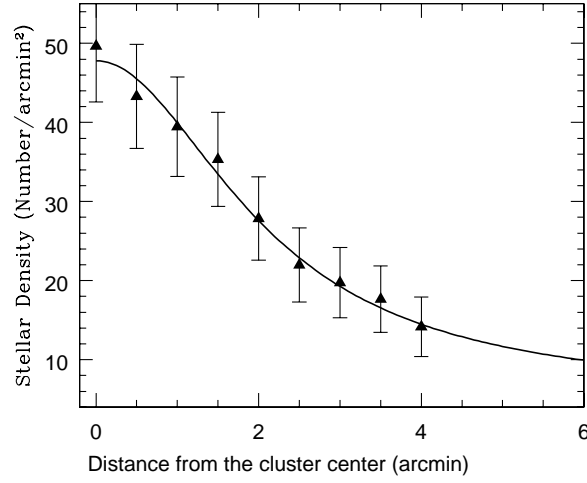


Fig. 2 The stellar radial density profile for stars brighter than 20.0 mag in the field of NGC 2141. The sold line denotes the King profile.

displayed in Fig. 3. We mark their positions on the CMDs and plot the Padova theoretical isochrones (Girardi et al. 2002) with the cluster physical parameters (age: $t = 1.9$ Gyr, metallicity: $Z = 0.008$, reddening: $E(B - V) = 0.36$ mag, distance modulus: $(m - M)_0 = 13.20$ mag) derived by Donati et al. (2014). Generally, stars in the open cluster distribute along with the isochrones. Two variable stars (V1 and V9) are far away from the isochrones. However, it is noted that the position of V1 in the CMDs settles in the main sequence but brighter than the turn-off stars. The current observations and binary evolution theories (Bailyn 1995; Lu et al. 2010; Geller & Mathieu 2011) showed that the cluster members are allow to locate at the area of V1. As a result, we concluded that all variable stars except for V9 are probably the cluster members.

4.2 Periodicity analysis

We used the PDM program in the IRAF-ASTUTIL package to determine the periods of variable stars, which is based on the phase dispersion minimization algorithm method (Stellingwerf 1978). To do this, we set a range of period to be 0.01-8 days. Then, we used the PDM program to estimate a few possible periods in the range and derive the corresponding phase-folded light curves. After visually inspecting the phase-folded light curves, we determined a best ones. Nine stars (V1-V9) were found to be the periodic variable stars and their periods and phase zero points are given in Table. 1. The phase-folded light curves are shown in Fig. 4. The light curves of V10 is shown in Fig. 5, in which the periodical variability is not found in our observations.

4.3 Classification and Discussions

We classified the variable stars, mainly based on the shapes of light curves, the detected periods and the positions in the CMDs. The classification and characterization of the variable stars in our study are discussed

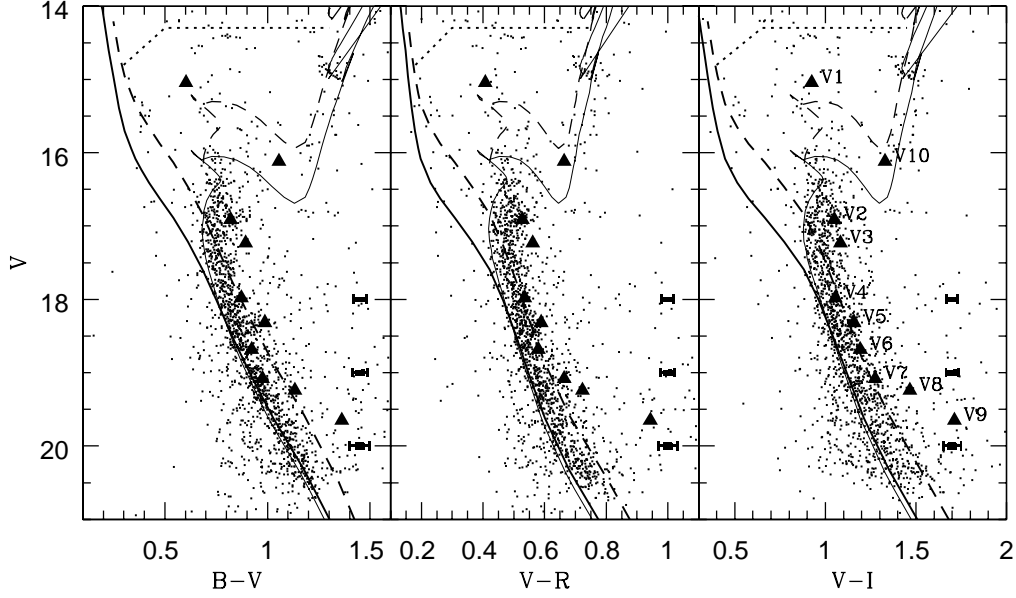


Fig. 3 CMDs of NGC 2141 and positions of variable stars in the CMDs. The thin solid lines denote the fit of the Padova theoretical isochrones with an age of $t = 1.9$ Gyr, a metallicity of $Z = 0.008$, an reddening of $E(B - V) = 0.36$ mag, and a distance modulus of $(m - M)_0 = 13.20$ mag (Donati et al. 2014) and the thick solid lines are the zero age main sequences. The dashed lines are the corresponding binary sequences. The dotted lines approximately indicate the upper edge of blue stragglers (Lu et al. 2010)

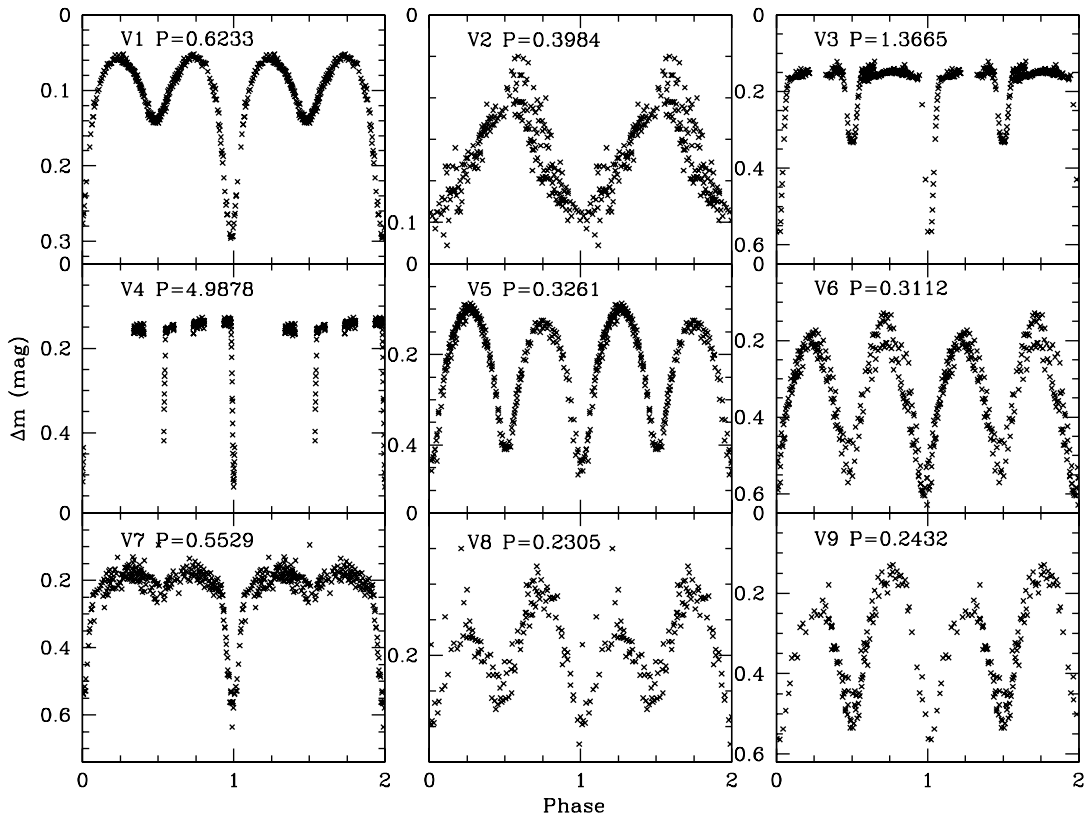


Fig. 4 Phased light curves of nine periodic variable star in the field of NGC 2141.

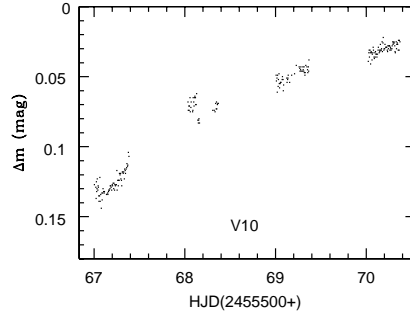


Fig. 5 Light curves of V10, an unknown type variable star in field of NGC 2141.

V1 has been classified as an EB-type eclipsing binary star by [Licchelli \(2011\)](#) and was named as VSX J060303.8+102715 in American Association of Variable Star Observers (AAVSO)¹. It is a likely cluster member and the period was updated as 0.6233 days. It is very interesting that V1 is more probably a blue straggler candidate of the cluster. The position of V1 in the CMDs is just in the region where the formation of the blue stragglers via the mass transfer have predicted ([Chen & Han 2008](#); [Lu et al. 2010](#)) and observationally many blue stragglers were found ([Geller & Mathieu 2011](#)). Our detailed photometric solution ([Luo et al. 2012a](#)) showed that V1 is a semi-detached binary with a less massive component that is filling the Roche Lobe and is super-luminance. Here, the discovery of V1 is prefer to support a conclusion that the blue stragglers in the open cluster origin from the mass transfer of binary stars ([Geller & Mathieu 2011](#)). Moreover, V1 is a rare eclipsing blue straggler binary system of the cluster that is transferring the mass from the less massive component to the massive ones ([Luo et al. 2012a](#)). Therefore, follow-up observations are important for investigating the physical process of the mass transfer during the formation of blue stragglers of the open cluster. The light curve of V7 is similar to V1. It is identified as an EB-type eclipsing binary star and the period was determined as 0.5529 days. In the CMDs, this star is located at the main sequence of the cluster binary stars. This star is also a likely cluster member.

V2 shows a peculiar light curve with slowly descending and quick ascending branches. The shape of light curves is similar to the RR Lyrae variable star. The most probable period was determined to be 0.3984 days, which is too long for normal δ Scuti star. Therefore, it is reasonable that V2 is classified as an RR Lyrae variable star. From Fig. 4, we can clearly see that the light curve appears obviously high asymmetry and rapid changes from one period to another. The period modulations can also be seen in phased light curves. These characteristics suggest that V2 is a d-type RR Lyrae star. The position in the CMDs is just on the main sequence, therefore, we could conclude that V2 is not the cluster member but a background field star.

V3 and V4 have a flat light maxima and are identified as the EA-type eclipsing binaries. They are the probable cluster member. The periods of V3 is estimated as 1.3665 days. However, the light curve of V4 was incomplete and the period is roughly determined to be 4.9878 days. Further observations are needed to ascertain the exact nature.

Table 2 Characteristic parameters of the light curves of four eclipsing contact binaries (V5, V6, V8, V9) $\Delta(\text{MinI} - \text{MinII})$ is the difference of primary and secondly eclipse, $\Delta(\text{MaxI} - \text{MaxII})$ is the difference of primary and secondly light maxima and A is the amplitude of light curve.

Star	$\Delta(\text{MinI} - \text{MinII})$ (mag)	$\Delta(\text{MaxI} - \text{MaxII})$ (mag)	$A \times 2$ (mag)	$\Delta(\text{MaxI} - \text{MaxII})/A$ (%)	period days
V5	0.06	0.04	0.38	21.1	0.3261
V6	0.06	0.05	0.47	21.3	0.3112
V8	0.03	0.07	0.22	63.6	0.2305
V9	0.02	0.09	0.23	41.9	0.2432

There are four short period eclipsing contact binary systems (V5, V6, V8 and V9) with the orbital period of $0.23 \sim 0.33$ days. The characteristics of their light curves are very similar. The light curves have a clear difference in depths of eclipses, in which the primary eclipses are deeper than secondary ones. Moreover, the light curves show the O’Connell effect (O’Connell 1951). The secondary light maxima are larger than the primary ones for V6, V8 and V9, on the contrary for V5. The characteristic parameters of the light curves are given in Table.2, from which we could find that the O’Connell effect increases with the decrease of the orbital period. This shows that the O’Connell effect is probably related to the evolution of the orbital period in short period eclipsing binary systems. The O’Connell effect of V8 is stronger than others, even more than 63 percent of the amplitude of light curve. Therefore, it is identified as the RS CVn-type eclipsing binary system. The others(V5, V6 and V9) have the general nature of the W Uma-type eclipsing binary system and are classified as the W Uma binary. However, the O’Connell effect in short period eclipsing binary systems is still uncertain. Many different theories have been proposed to explain to this effect, but no one theory have been successfully applied to more than a handful of binary systems (Wilsey & Beaky 2009). Further multi-color photometry and spectroscopy observations may put some insights into the nature of the O’Connell effect in eclipsing binary system.

V10 is classified as an unknown type variable star. The time-series light curves does not show any periodical variability in our observations. Further observations will help us determine their periods and physical properties.

5 SUMMERY

In this paper, we have presented a time-series V band and muti-color $BVRI$ CCD photometry for the open cluster NGC 2141, undertaken in 2011 to detect variable stars. The following conclusions can be drawn:

1. Ten variable stars have been detected in the field of the old open cluster NGC 2141, among which nine are newly discovered. We discussed their memberships on the basis of their space locations, positions in the CMDs, and physical properties. Seven stars (V1, V3, V4, V5, V6, V7, V8 and V10) are the probable members of the cluster, while the others (V2 and V9) are the unlikely cluster members. We found that nine stars are the periodic variable stars and their periods were determined with the phase dispersion

2. We assessed the classifications of variable stars and discussed the physical properties, primarily based on the shape of light curve, the detected period and the position in the CMDs. They are categorized as three W UMa-type eclipsing binaries, two EA-type eclipsing binaries, two EB-type eclipsing binaries, one d-type RR Lyre star, one RS CVn-type eclipsing binary and one unknown type variable star. A known EB-type eclipsing binary V1 settles in the area of the cluster blue straggler in the CMDs and it is identified to be a blue straggler candidate.
3. In this study, we found that all four short period eclipsing contact binaries show a clear difference in depths of eclipses and O'Connell effect which increases with the decrease of the orbital periods. This illustrates that the O'Connell effect is probably related to the evolution of the orbital period in short period eclipsing binary systems.

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